Key Issues Regarding the Origin, Nature, and Evolution of Complexity in Nature

Information as a Central Concept to Understand Biological Organization

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Human beings are used to building, maintaining, and managing complex structures and organizations. The development of language, technologies, societies, and so on has made it possible. This could lead us to think that the generation of complexity is not a big issue. However, whenever we try to make complexity develop in a scenario where there is no human presence, nor any possible intervention of other living organisms, things become much harder. Yet most of us are convinced that there had to be a time when matter “itself” progressively turned into more and more elaborate forms of organization, eventually into some sort of biological organization, initiating a process of evolution out of which humankind (only very recently) arose. Thus, it seems necessary to understand the spontaneous origins of complexity in nature if we really want to grasp its actual meaning and its relevance as a scientific concept.

Some important steps have already been taken along those lines. During the last decade we witnessed the development of the “science of complexity” (Waldrop, 1992), even if rather diverse conceptions of complexity have been put forward in the literature, and nowadays there is still no clear consensus on how to define the term. A rather widespread view considers complexity as a phenomenon universally present wherever densely interconnected sets or networks of elements/components are established (Weaver, 1948; Simon, 1969; Kauffman, 1993; Horgan, 1995). According to this view, the study of complexity would basically consist of understanding and specifying the conditions under which certain sets of components cross a critical point or threshold of interconnections, triggering the emergence of new global properties. This kind of phenomenon occurs in such a broad variety of systems (physical, chemical, biological, ecological, neural, social, computational, and so on) that it can certainly be regarded as universal.

However, this generic way of conceptualizing complexity misses a very important point: It does not address the problem of how complexity can be preserved and, furthermore, how it can increase indefinitely in time. In other words, it focuses on identifying the most basic spontaneous processes of generating complexity (at different phenomenological levels), disregarding what could cause a longer-term maintenance or evolutionary growth of that complexity. But, quite interestingly, most of the complexity that surrounds us today is the result of previous forms of complexity, which have developed the capacity to endure and evolve through time.

The fundamental problem to be tackled in the following pages is how such a special type of complexity (complexity with potential for evolutionary growth; McMullin, 2000) can be characterized in general terms. In order to do so, we will have to search into the origins of minimal selfmaintaining systems that develop mechanisms to self-produce and self-reproduce*reliably*. In particular, we will have to focus on how the issue of generating complexity becomes entangled with the issue of preserving it, in an ever more efficient way. This is quite tricky because, as the level of complexity in the system increases, its preservation, in principle, also becomes harder and harder. What kinds of mechanism are necessary and sufficient to allow the appearance and maintenance of progressively more complex forms of organization?

Biological and human organizations (like social systems) constitute the only type of system we know that can generate and increase complexity indefinitely. In the course of biological evolution there has been a “nonstop” generation of new forms of metabolic organization, of increasingly complex internal restructuring processes, and many different types of adaptive interactions (with the environment and with other organisms) have also appeared, some of which led to the development of cognitive capacities (through the invention of a nervous system). At the level of human organizations, cultural evolution has also shown a constant yield of new and “ever more complex” arrangements of social communities and structures. Despite the many—and important—differences between all those various systems/phenomena, there is a fundamental mechanism common to all of them, as we will try to show below. In this article we will focus on the origins of this mechanism at its most basic level. Therefore, our analysis will be carried out in the context of the transition processes that lead from the most primary self-organizing phenomena to new and progressively more complex forms of organization.

PRODUCING AND PRESERVING COMPLEXITY: TWO DIFFERENT (THOUGH RELATED) PROBLEMS WITH DIFFERENT (THOUGH RELATED) SOLUTIONS

The central question to be posed here is, therefore, which material structures—and under which conditions—can generate “open-ended” complexity, complexity that may indefinitely vary and grow. The idea is to formulate this question not only in generic terms but also, so to speak, in basic terms. That is, we are searching not only for a universal set of mechanisms through which that “open-ended” evolutionary process can be achieved, but for the simplest universal set. As we already mentioned in the introduction, this problem shows two main sides: first, specifying how it is possible to establish a continuous, unlimited process of *production* of complexity; and, second, finding out the way in which that complexity (or part of it) becomes capable of ensuring its long-term *preservation*. It is convenient to distinguish these two aspects of the problem, even if they turn out to be deeply interrelated. Typical self-organizing phenomena, for instance, create some dynamic complexity but are not good at preserving it (without external aid, that is), whereas certain growing crystals keep their structural complexity with a very high degree of reliability, but are strongly limited in generating novel complexity. In this article we will investigate systems that can create by themselves “ever new” complexity as well as preserve it reliably.

In that sense, we can safely say that the production of complexity by any physical, real system requires material and/or energetic resources. This might be at stake for systems that tend toward thermodynamic equilibrium, but the complexity that such systems can show is rather low (and, more significantly, the complexity to which they can ever give rise). A frozen pattern may be very elaborate, while it constitutes merely an inert sign of the actual dynamic phenomenon that brought it about. As a matter of fact, the complexity of conservative structures may be very high, but only in a “formal” sense, since it hardly generates causal differences in the behavior of the system. Here we are interested in processes with the potential to produce operational, functional complexity (i.e., not only structural but also organizational; see below) in a continuous and indefinite way. Since this kind of “dynamic complexity” can only take place in far-from-equilibrium conditions, where nonlinear, long-range correlations between different processes can be established, we are forced to deal with (thermodynamically) open systems, in continuous interaction with their environment.

This is clearly the case for self-organizing phenomena like “dissipative structures” (Nicolis & Prigogine, 1977), in which complex patterns of order are indeed created. Long-range connections/interactions among the basic components/processes of the system (plus the constant flow of matter/energy through it) are responsible for the appearance and maintenance of that pattern. However, in these phenomena the production of complexity is severely limited. Physico-chemical self-organizing processes depend too much (or too critically) on external boundary conditions: They do not have any control over the material-energetic resources necessary to create complexity, so that when these disappear, or vary significantly, the processes decay.

So how does a dissipative, self-organizing system become more robust and capable of acquiring by itself the material-energetic resources required for its maintenance? A fundamental requisite is that the selfmaintenance of the system becomes recursive and modulable (Bickhard, 1993). This is only possible if the dissipative organization of the system develops a remarkable degree of plasticity, which allows some primitive and very basic *functional-adaptive* behavior, as well as the capacity to define the domain of interactions with the environment. Thus, the first step that may be taken to tackle our central problem involves the introduction of the concept of “functionality,” that is, consideration of the causal role that the components of a system may have in its maintenance as a whole, and, thereby, in their own maintenance as components. This, in fact, is the main idea underlying Rosen’s conception of complexity, for instance. He defines a complex system as that in which the presence and activity of each component cannot be explained but by resorting to the internal efficient causal interaction in the system (Rosen, 1991). This is an important concept for two different reasons: on the one hand, because it directly connects the degree of complexity of the system with the problem of its maintenance or preservation; and on the other hand, because it also connects it with the problem of the “identity” and the clear-cut distinction between system (operational unit) and environment. The need for plasticity implies that the type of system to focus on must be *chemical*, for physical systems in general do not have the capacity to create a wide enough variety of dynamical constraints.

In contrast, chemical systems are a special kind of dynamic organization in which the construction of new molecular variety through *dissipative processes* creates new *conservative constraints* (molecular shapes), which, in turn, can modify the whole organization (and this new organization can bring about new molecules that may produce new forms of organization recursively). An additional reason is that purely physical dynamics (i.e., behavior strictly related to the change of position of a body, or of the many bodies that may constitute a system) is not sufficient, as such, to provoke phenomena in which complexity can be produced indefinitely and with a minimal potential to grow. There are examples of physical self-organization (e.g., the Bénard convection cells) where a very complex pattern of order is created. Yet these systems or processes do not show possibilities to overcome the level of complexity already achieved. In other words, the jump from physics to chemistry seems necessary for material systems to have within their reach a diverse enough spectrum of dynamic, constructive, and emergent behavior.

Thus, the kind of active self-maintaining system required to establish a continuous and indefinite production of complexity must be a chemical system that acquires some control over the boundary conditions that allow the productive processes to begin in the first place, and simultaneously manages matter-energy flows so as to keep those processes running. In this situation, the processes of producing complexity are actually the processes constituting the components of the system, and the system as a whole (boundaries included). In other words, the (chemical) identity of the system is its own productive activity; its “being” is no more—nor less—than its “doing” or “making.” Elsewhere (Ruiz-Mirazo & Moreno, 1998, 2000) we have argued that the emergence of this kind of system is feasible, and that its most characteristic or defining property is “basic autonomy.”

THE LONG-TERM MAINTENANCE OF AUTONOMOUS SYSTEMS

The constitution of systems with an autonomous machinery to construct (and reconstruct) all their material components serves to solve a good part of the problem of establishing a continuous process of producing complexity, since their adaptive self-maintaining organization allows, in principle, unlimited generation of new functional components. Nevertheless, merely by itself this kind of system is not capable of realizing all that potential. By means of a self-constructing organization—autonomous and at the same time necessarily open and interactive—it is possible to create ever new components and ever new relations among them, some of which will certainly involve an increase in complexity. However, this solves neither the problem of preserving the complexity that emerges in the process, nor the problem of how this complexity could grow indefinitely.

Of course, the productive and reproductive dynamics of an autonomous (proto-metabolic) network would contribute to maintaining the structural and organizational complexity achieved by the system, as a cohesive set of components—and aggregates of components—functionally interconnected. However, this still rudimentary functional dynamics cannot ensure that the components (together with their way of organization) remain unaltered for much longer than their typical "lifetimes" (or the typical lifetime of the whole organization), and the system faces a serious bottleneck: As complexity rises, its preservation becomes more and more difficult. Therefore, basic autonomous systems have to develop specific mechanisms to stabilize and retain the structural and organizational complexity that they create. Only once they become capable of preserving that complexity with a fairly high degree of reliability can they begin unfolding new, subsequent levels of complexity and, furthermore, set up the first pillars to ensure their *long-term* maintenance as an emergent kind of natural system.

So the first step that basic autonomous systems have to take in order to retain the complexity they create is to establish some mechanism through which the structural-functional properties of the most complex—and typically most fragile—components can be preserved (otherwise the specific organization of the system would very soon get lost). This cannot be accomplished without some sort of "template" or "blueprint" copying device; that is, without some local and robust material mechanism ensuring the renewal (initially only by *direct replication*) of such complex components.

However, the preservation of increasingly complex functional components through some template mechanism requires a very special type of component. This must consist of a chain of interchangeable discrete units, which form a specific one-dimensional (1D) sequence, and whose global three-dimensional (3D) shape allows the recurrent copying—by chemical complementarity—of complete equivalent sequences, in such a way that the system achieves a highly reliable way of synthesizing specific molecular chains and, thereby, of maintaining the functional properties associated with those chains. In fact, it is only when autonomous agents start producing complex molecular aggregates capable of fixing and transmitting their basic sequence (and, thereby, their structural and functional properties) that it becomes significant to introduce concepts like "memory" or "heredity" in the description of the system (Pattee, 1967).

Thus, we are not talking here about simple template components, like the ones present in the growth of a crystal, for instance. Rather, the type of molecular structures that may act as real material *records* of an autonomous organization must be modular templates. That is, they must be polymers that fulfill the following two conditions: First, their building blocks or basic subunits must be big enough to have three molecular groups, needed to establish the different bonds that will allow their actual constitution as a modular chain and the linkage with other basic subunits in the process of producing a copy or complementary chain; and second, the 3D structure into which these components fold must not be altered significantly as a result of particular changes in the sequence of subunits (since this will seriously threaten their capacity to replicate by template), which implies that the states associated with the different sequences of subunits must be, energetically speaking, almost equivalent or *quasidegenerate*.

This implies that the material basis of records or modular templates must be different from the functional units controlling/regulating precisely the processes that make up the complex network of production of components (i.e., the metabolism that actually constitutes the system). The reason behind this incompatibility has to do with the structural limitations of any system based on a single type of polymer (like those systems put forward by Benner, 1999). Indeed, the capacity to store and replicate sequential complexity increases as the capacity to express sequential variety in 3D variety—diversity of shapes—decreases (see Moreno & Fernández, 1990). In fact, the latter is the key to the dynamic/functional organization of the system, since the fine-tuning of chemical rates depends crucially on the stereo-specific features of the molecules involved. Therefore, it becomes necessary to convert the sequential complexity present in the chain of subunits making up the template components into another kind of subunits or building blocks, apt to integrate chains whose 3D structure expresses their sequential differences. All this amounts to saying that this new kind of autonomous, self-constructing organization requires two types of modular (macro) components, made up with different molecular subunits.

In a—possibly previous—scenario with a single type of complex polymer (e.g., in an RNA world type of scenario), the conversion from the sequential pattern to the functional feature is rather direct (it merely involves the folding of the macromolecular chain that constitutes each component). However, at this stage the system is forced to develop two different, though complementary, modes of operation, so the situation is more intricate: The connection or interrelation between 1D stable sequences and 3D functional configurations cannot be articulated by mechanisms merely founded on the physico-chemical affinities between the subunits of such different components (for instance, through some base-pairing mechanism). How can this be achieved?

The solution is to set up an indirect, mediated relationship in which the records *instruct* the synthesis of the functional components; and these, in turn, control and catalytically regulate all the processes in which the records are involved (replication, translation, reparation, etc.), even if they do not take part directly in the creation and alteration of those records. The key lies, therefore, in the establishment of a certain circularity (causal correlation) between the two operational modes so that the system can "self-interpret" the sequences of the records. Pattee (1977) carried out a thorough and insightful analysis of this kind of material organization where there already exist two quite different levels of operation, one involved in the system's fundamental productivemetabolic processes (i.e., "dynamic," "rate-dependent" processes); and the other, partly decoupled from all that muddle of chemical reactions, putting together a group of special processes and components ("rateindependent" processes), with particular rules of composition and functioning.

This *decoupling* turns out to be fundamental from the organizational point of view, since it allows the recruitment for/by the individual of autonomous systems of the results (end products; selected patterns) of a slow, much more encompassing process of natural selection taking place outside these individual autonomous systems. The changes that take place at the level of the records are largely independent of (decoupled from) the dynamical processes of the system that these components instruct. In particular, the instructive content of the records must be determined by the evolutionary process in which the whole population and its environment are involved, not by the metabolic dynamics of each of the agents within it. And precisely when the system incorporates and integrates inert records as fundamental components in its operational organization, components whose linear-sequence configuration is not directly linked to the dynamic processes of metabolism, it becomes possible that those sequences act to causally control and specify the synthesis of new and more complex functional components.

In this way, through the emergence of a new type of metabolic organization (that we could call "instructed metabolism"), autonomous systems can combine coherently and consistently the individual dimension of their activity (related to the self-construction/self-maintenance of each) with a progressively more important collective dimension (related to their long-term maintenance and evolution as a whole population).

LINKING THE INDIVIDUAL AND COLLECTIVE SPHERES: THE ORIGINS OF INFORMATION

The most natural and convenient way of understanding this new ordering in the system is through the idea of *information*, meaning a causal mechanism that operates to infuse or propagate *forms* and whose final effect is to restructure selectively the organization of a material system (Moreno, 1998). We should highlight here that the causal implications of the term "form" go beyond the intrinsic way of matter to self-constrain and restructure itself, as in the case of those stable patterns self-maintained by means of selective action on the constituents of the lower level (Van Gulick, 1993: 251-2).

What is most relevant about the causal action of information is that those forms are explicit, in the sense that they consist of discrete units realized on a material basis (or material carrier) that transcend the individual system where they operate; and that there is no direct—material— causal link between those structures carrying the information and the structures whose configuration is selectively modified by the former. Information is thus a special type of formal causation, in the sense that it infuses or propagates structures (and, indirectly, organizations), but in a way that is dynamically decoupled from the system that it constrains. It is an explicit, rate-independent, formal causation, not a mere selfconstraining rate-dependent mechanism based on a dissipative kind of organization. Accordingly, we can say that information is founded on material structures that allow compositional or syntactic-like processes, processes that are dynamically decoupled from the level of the system where the information operates.

We can certainly see that this concept of information serves adequately to characterize the type of organization described in the last section. The sequential pattern of discrete units making up the records, in so far as it acts as an instruction to specify the sequence of subunits that will constitute the functional-catalytic components, appears as a purely formal constraint, for there is no direct causal relation between the materiality of one and the other kind of subunits/components. What is crucial in that causal relation is *form* itself. Moreover, it is a type of form that, due to the nature of its material basis, stays somehow decoupled from the (individual) system where it operates causally; it does not really originate in that system, nor does it normally disappear with it.

Let us analyze more thoroughly the main reasons that it is suitable to apply the concept of information to account for the autonomous organization whose emergence has been roughly explained above:

1. The system is producing discrete, digitalizable structures—which here we are calling “records”—whose accessible states are highly degenerate (i.e., all possible sequences or linear configurations have similar energy levels and thus are, in approximate terms, equally likely) and, accordingly, they have a high degree of *compositionality* (capacity for multiple processes of—almost free—combination with other similar structures).

2. The system as a whole creates (and depends on) an arbitrary, noninherent (but stable) relation between the sequence of the records and the functional components whose synthesis is instructed by them, so that a *translation code* is required to link the sequential configurations of records and the building blocks of their corresponding functional components. Accordingly, there exists an indirect link between a given form—the 1D sequence of the records—and the dynamical processes controlled by the complex functional component—by means of its 3D configuration/stereo-specific properties—whose construction is instructed by the former.

3. These 1D sequences behave as “formal syntactic” structures because they achieve a high degree of decoupling from the intrinsic dynamics and physico-energetic conditions to which their particular material basis is subject (i.e., they establish their own rates and their own processing rules, and remain in an inert, passive, referential state). Hence, there is a dynamical decoupling between two kinds of (complementary) processes in the system: those concerning the formal structure of the records, which appear as rate independent, and those concerning its causal effects (its expression), which appear as rate dependent.

Ultimately, this decoupling is the expression of a radical insertion of autonomous systems into a historical-collective network (an ecosystem) where the “slow” processes of creation and modification of informational patterns take place, and where an additional circular relation of cause and effect is established between the individual metabolic organizations and the eco-evolutionary global organization. *The origin of information (of genetic information) takes place precisely when the link between both dimensions is articulated*.

Therefore, the generation of an informational machinery seems critical for the increase in complexity of primitive types of autonomous systems, toward novel systems whose more complex attributes will be developed through the operation of records. Provided that the sequences responsible for the production of functional components (which will be realized in each individual system) become explicit, and their specific “form” is generated in the course of processes that are independent of the internal dynamics of the system where they operate (processes that involve many generations of such systems and, thus, take place at a different spatial-temporal scale), we can safely state that the construction of new, increasingly complex systems turns out to be fully open ended. It is not until then that autonomous systems can put into practice a radically different way to change and innovate, in which the variations of the records (i.e., the mutations, the new combinations of sequences, etc.) take place free of the constraints of dynamical and functional character. Consequently, the evolutionary process that these systems begin may be regarded as the laboratory where new informational sequences are built up, out of which natural selection will only pick or retain those whose expression gives rise to apt and viable organisms.

CONCLUSION: INFORMATION AS A UNIVERSAL REQUIREMENT FOR OPEN-ENDED EVOLUTION

The great relevance of information in increasing the complexity of material systems lies in the fact that it constitutes a new and very powerful tool or machine, which allows the establishment of new causal connections between domains that are not necessarily linked by physico-chemical laws. Although we can already identify in self-organizing and autonomous systems some kind of “recursivity” through which it is possible to establish such physically “noninherent” causal connections in a basic individual system, without the advent of informational records these emergent causal connections are fully dependent on the actual dynamic organization that they contribute to maintaining. As we have said throughout this article, in these conditions the growth in complexity of the system comes together with a growth in fragility, which implies a serious evolutionary bottleneck.

In contrast, the appearance of information brings forth a radically new level of organization, since it makes possible for a great number of causal specifications to be assigned to some inert components decoupled from the dynamical organization of the system. As a result, those specifications will, in principle, be independent of the dynamic and energetic conditions implied by their material expression. It is precisely their decoupling from the dynamics of the system that endows those components with compositional properties. Thus, it becomes evident that underneath the restructuring capacity of informational causation is found a mechanism of dynamic decoupling.

As we have seen, this mechanism operates for the first time in the reorganization of the processes of self-maintenance/selfproduction in prebiotic metabolisms, in which some *genetic* components start to act as dynamically inert material instructions for the synthesis of specific *functional-catalytic* components. This is the origin of life understood as an evolutionary aperture, as the opening opportunity for autonomous systems to increase indefinitely in complexity.

Nevertheless, in the course of biological evolution, this fundamental mechanism has been subsequently used or applied to allow and articulate different major transitions. In particular, we can see that it must also be operating at the origins of cognition, at that stage when some multicellular organisms (those whose way of life was based on movement) developed new forms of complex behavior by means of the decoupling between their adaptive-interactive strategies and their actual metabolism (giving rise, later, to the whole complexity of the cognitive phenomenon; Moreno *et al.*, 1997). More recently (always relatively speaking), we can also find other—perhaps more intuitive or clearer—examples in the evolution of human organizations. For instance, the invention of written language constituted a mechanism that allowed a great increase of social organizations thanks to the decoupling of the method of storing information from the bio-neuronal processes running in each human being; or, in a somewhat different context and with different implications, the development of mathematics and the empirical sciences was made possible thanks to the creation of formal languages through which certain operations/calculations could be carried out decoupled from all empirical connotations.

In conclusion, the principle of dynamic decoupling within a complex integrated system probably constitutes the most basic mechanism for reorganizing that system in a way that makes possible the growth in its complexity at the same time as it allows it to keep the level of robustness required for its maintenance, reproduction, and evolution. Without this fundamental mechanism, there would be no solution to the problem of the increasing fragility associated with the growth of complexity (as the level of complexity rises in the organization there is a higher and higher risk of destruction by perturbations), so nature would not be able to overcome a (prebiological) threshold of complexity. Furthermore, without this mechanism, complex systems would not be capable of carrying out any transition involving some radically new restructuring of their organization.

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